

Pupil dilation during visual target detection

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It has long been documented that emotional and sensory events elicit a pupillary dilation. Is the pupil response a reliable marker of a visual detection event while viewing complex imagery? In two experiments where viewers were asked to report the presence of a visual target during rapid serial visual presentation (RSVP), pupil dilation was significantly associated with target detection. The amplitude of the dilation depended on the frequency of targets and the time of target presentation relative to the start of the trial. Larger dilations were associated with trials having fewer targets and with targets viewed earlier in the run. We found that dilation was influenced by, but not dependent on, the requirement of a button press. Interestingly, we also found that dilation occurred when viewers fixated a target but did not report seeing it. We will briefly discuss the role of noradrenaline in mediating these pupil behaviors.

Keywords: search, detection/discrimination, attention

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Introduction

The relationship between pupil dilation and mental or emotional events has been reported for more than a century, starting with the work of Charles Darwin in 1850 who investigated the effect of emotion and fear in humans and animals (Darwin, 1850, see also Beatty, 1982; Clark, 1885; Hess, 1975; Kahneman, 1973, and, more recently, the review of Steinhauer, 2002).

Pupil size and dilation have been studied in relation to cognitive processing of visual information. For example, when subjects view ambiguous visual stimuli, pupil dilations were reported in anticipation of the rivalry switch and reflect the duration of perceptually rivalrous states (Einhäuser, Stout, Koch, & Carter, 2008). The emotional content in the visual stimulus might trigger a proportional pupil reaction as documented by Steinhauer, Boller, Zubin, and Pearlman (1983) who showed that highly aversive or pleasant pictures were associated with

large dilations. During visual-motor operations with a computer, the subject gains information about her task and thus changes her point of view, thinks of different goals, or modifies her scanpath or general behavior. This cognitive event (or task shift) is correlated with a series of abrupt pupil size enlargements over a period of time (Marshall, 2002; Marshall, Pleydell-Pearce, & Dickson, 2003). Task-evoked pupil dilations are widely reported in the literature (Beatty, 1982; Juris & Velden, 1977; Karatekin, Couperus, & Marcus, 2003) and the magnitude of the pupillary dilation appears to be a function of the cognitive workload and attention required to perform the task (see also Goldwater, 1972; Granholm, Asarnow, Sarkin, & Dykes, 1996; Hoecks & Levelt, 1993; Iqbal, Zheng, & Bailey, 2004; Janisse, 1977; Porter, Troscianko, & Gilchrist, 2007) and it could even reflect the general cognitive performance of individuals engaged in complex visual tasks (Verney, Granholm, & Marshall, 2004).

To the best of our knowledge, the only study that specifically recorded the pupil response during visual

target recognition is the work by Hakerem and Sutton (1966). Their data indicate that the neuronal mechanisms underlying the pupil light reflex (which triggers a constriction) were less sensitive than those mechanisms controlling the dilation in a detection threshold task. Using simple light stimuli targets, they found that pupil dilation occurred when light pulses were perceived and only when subjects were required to make a discrimination.

Normal visual search in natural active looking is a complex set of component processes that may be compartmentalized into two interleaving phases of scanning and detection (Privitera & Stark, 2003). Eye movements drive the fovea to fixate each part of a scene to enable processing with high resolution. Each fixation involves bottom-up signal processing and top-down higher level operations such as semantic binding and symbolic association of visual memory, which are basic to recognition (Privitera & Stark, 2003; Stark et al., 2001). The rapid serial visual presentation protocol, RSVP, with a central fixation point is intended to simulate the rapid alternation of foveated regions of interest during normal viewing conditions while eliminating several complications due to tracking the pupil size during eye movements. Using the RSVP protocol, we have recorded the pupillary response during visual search with complex imagery. Under these conditions, we found that pupil dilation was associated with target detection even when subjects were not required to make an overt discrimination. This result differs from that of Hakerem and Sutton (1966) where dilations were not reported for the same condition.

Habituation involves decreased sensitivity or response strength with repeated stimulus presentations. During visual search does the pupillary response habituate to repeated target occurrences? In the RSVP protocol, habituation was explored by both examining the average response magnitude for different target frequencies or density across image sequences and also by noting response strength as a function of time from a sequence onset. In both cases, evidence is presented in support of pupillary response habituation.

Finally, while a button press response to a detection event is typically a binary variable, reflecting a decision and motor stage criterion, the pupillary response is a continuous variable and can be dissociated from the behavioral response. Could the viewer only be subconsciously aware of the target, and yet, the pupil still reflects its presence? In our experiments, we found dilations even when viewers did not report seeing the target that had been fixated.

We used two different types of stimuli corresponding to two different aspects of vision recognition and processing load. In the first experiment, visual targets were not explicitly defined: the meaning of the object but not the specific object itself was explained to the subjects. We call this *semantic* visual detection because it involves a mental operation aiming to bind the pure visual information of the viewed object with a given meaning expressed in a

nonvisual language. In the second experiment, targets were well defined and an example was shown to the subjects prior to the experiment. We call this *iconic* visual detection since it implies a direct matching between the mnemonic and iconic cognitive representation of the target and the bottom-up information generated by the foveation. We believe that these two cases are associated with two different levels of visual processing and resemble two typical conditions in natural vision.

The synergy of the two pathways that operates on the two smooth muscles composing the pupil, the parasympathetic and the sympathetic nervous system, will be discussed in the [Discussion](#) section with emphasis on the modulating role of locus coeruleus in the brain stem.

Methods

Two experiments were designed to examine the pupil responses associated with object detection under visual search conditions with limited image viewing time. In both experiments, the stimulus computer monitor was the only source of illumination in the environment surrounding the subject, consequently, the pupil operated approximately in the middle of the iris muscle length–tension curve where the relationship between excitation and amount of muscle response is linear. This was to avoid the mechanical muscle saturation at the two extremes of the pupil size where a significant amount of input excitation may generate undetectable pupil responses. Subjects performed the experiments in a booth that isolated them from the surrounding laboratory. The booth contained a chair and desk with the stimulus monitor and the eye-tracker apparatus. The EyeLink 1000 head supported eye-tracker system (http://www.sr-research.com/EL_1000.html) that has a temporal resolution of 1000 Hz was used to track eye position and collect pupil diameter. Eye blink artifacts detected by the eye tracking software were automatically removed from the pupil data. The corresponding affected parts of the pupil record were recovered with cubic interpolation. Few trials (circa 5%) were discounted after visual inspection of the pupil waveform for excessive blinking.

The frequency response of the pupil servomechanism is characterized by a break frequency at approximately 2 Hz (see the pioneering work of Stark & Sherman, 1957 and more recent results in Privitera & Stark, 2006); accordingly, pupil data were low-passed using a Butterworth filter with a cutoff frequency of 4 Hz.

Experiment 1: Semantic target detection

Subjects and apparatus

Ten subjects (six males) participated in the experiment and ranged between 25 and 65 years old. They had no

particular training in viewing the type of images and image presentation used in this study. No signs of eye disease or neurologic illness were reported. They were all screened for visual acuity sufficient to distinguish small details at a viewing distance of 30 cm from the display monitor without wearing eyeglasses.

Stimuli

Visual stimuli were a sequence of 100 simple iso-luminant object icons (Figure 1) displayed at the center of a uniform white background and subtended approximately 2 degrees of visual angle at a viewing distance of 30 cm. Iso-luminance was achieved by normalizing the pixel levels integration of each icon to the same intensity of approximately 70 cd/m². The luminance of the monitor used for the experiment was linearized using a WinVis linearization routine (www.neurometrics.com/winvis), and, as mentioned above, the monitor was the only source

of illumination. The set of visual icons contained different groups that could be semantically associated. We defined three classes: (1) a class of objects that could be associated to the meaning of music (i.e., a note or trumpet, Figure 1), (2) a class of objects that could be associated to the meaning of brain (i.e., a dog or a dolphin), (3) a class of objects that could be associated to the meaning of holiday (i.e., a Santa Claus stocking or a candle with Christmas holly). Since the same set of image was used irrespective of the icon class, possible residual luminance artifacts were balanced across target–nontarget conditions.

Procedures

Each participant was instructed to look at the center of the screen and to avoid blinking. When an object that could be associated with the prespecified meaning is presented, the response button was pressed. For each

Examples of targets for music Examples of targets for brain Examples of targets for holiday



Experiment 1 –
Semantic detection



Experiment 2 –
Iconic detection

Figure 1. Examples of target associated to the three different semantic classes of Experiment 1 (top, Experiment 1 imagery is from nesoft.org). All images were preprocessed prior the experiment and made iso-luminant (pixel brightness integration was constant for all stimuli); they subtended approximately 2 degrees of visual angle and they were alternated every 0.7 s. For Experiment 2, targets were helipad sign in the center of a satellite photo (bottom right); an example of a nontarget image is also reported (left, Experiment 2 imagery is from DigitalGlobe). The locus of eye fixation was maintained at the center of the computer stimulus monitor and stimuli were rapidly alternated at 10 Hz.

participant, the 100 icons (target and nontarget) were displayed in succession in the center of the screen for 0.7 s in random order. The object class to be used as a semantic target (*music* or *brain* or *holiday*) was randomly selected for each subject and specified immediately prior to the start of the experiment. Five of the ten subjects repeated the experiment with a different semantic target; this time they were instructed to simply count the targets and report the number at the end without pressing the button.

Experiment 2: *Iconic* target detection

Subjects and apparatus

Seven subjects (six males, 30–50 years old) participated in the second experiment. They were professional image analysts trained to visually analyze satellite images. They were all familiar with the type of images and the characteristics of the target used in the experiment. They were also familiar with the viewing conditions where intense mental focusing on the task and rapid responses were essential.

Stimuli

Stimuli were wide area high-resolution gray-level satellite photos of urban and rural areas from which we extracted a sequence of about 3000 nonoverlapping image “chips” of 500×500 pixels, each subtending approximately 10 degrees of visual angle. The loci of the targets within the high-resolution photo were provided with the satellite image data set; image chips were extracted top-down and left–right; for targets, the image to be extracted was shifted a little in order to place the target on the center of the image, all the neighbor images shifted to avoid overlap. The WinVis stimulus delivery software (www.neurometrics.com/winvis) ensured presentations free of frame drops, recorded behavioral responses, and provided synchronization pulses to align eye and pupil tracker and button press data with stimulus presentation (Carney, Ales, & Klein, 2006). Image chips were presented in rapid serial visual presentation, RSVP, at 10 Hz (100 ms/chip) at a screen refresh rate of 60 Hz. Such time is usually sufficient for human observers to complete sophisticated object discrimination (see, for example, Keyser, Xiao, Foldiak, & Perrett, 2001). The experiment was divided in separate viewing sessions, each one lasting approximately 120 s (though we also performed some longer experiments of about 3–4 min of viewing) for a total of 1200 image chips. Each satellite photo required usually 2–3 viewing sessions. The target chips contained a helipad centered on a chip and usually located atop a large building in an urban setting. The size and orientation of the helipads varied as well as the background or surrounding in which the helipad was embedded. Figure 1 shows

sample target and distracter image chips. A small fixation marker was present during the image presentation sequence. The frequency of image chips containing helipads varied from session to session and they uniformly ranged from a low density, average of one target every 60 s, to a high density, up to approximately an average of one target every second.

Procedures

Viewers were asked to remain fixated on the fixation point in the center of the monitor during image presentation and to promptly report, with a button press, the presence of helipad targets. The seven viewers completed at least thirty different viewing sessions, which extended over 2 days for most of the viewers. Each session was characterized by its target frequency and the image chips in each sequence were always unique. Image chips were centered on the screen with gray surround, which maintained the baseline pupil size in the low–middle range of 3–4 mm for all subjects. Each viewing session was preceded by a few minutes of rest during which the subject could sit back and relax.

Illumination function estimation

The brightness fluctuations of the screen during stimulus presentations can generate pupillary responses that were to be differentiated from the target detection-driven dilations. The screen luminance was calibrated with a photometer located at the distance of the subject’s face during the experiment. Since the pupil light reflex sensitivity peaks at the foveal location and decreases toward the periphery (see, for example, Hong, Narkiewicz, & Kardon, 2001), a centered 2D Gaussian (1 degree standard deviation) weighted mean of luminance was calculated for each image chip. The temporal progression of image chips created a sequence of these foveal brightness intensity values, which defined a temporal illumination function that was low-passed for our analysis using the pupil bandwidth parameters (4-Hz low-pass filter) discussed above in this section.

Key-press-not-required condition

Similar to Experiment 1, we asked a smaller group of subjects (three for Experiment 2) to repeat part of the second experiment using the same type of stimuli and experimental protocol but without the button press requirement. These three subjects were instructed to look at the sequence of images, being aware that it was similar to what they already viewed earlier during experiments with button press and to simply keep looking for targets. The objective was to investigate a possible correlation

between pupillary response and the initialization and execution of the button press motor task (which was eliminated in this last condition).

Results

The raw pupil diameter as a function of time revealed the typical random fluctuations often referred to as pupil unrest. This physiological fluctuation is correlated between the two eyes and is also correlated to brain activity (Stark, Campbell, & Atwood, 1958). Nevertheless, a pupil dilatation is often detectable right after target presentation (Figure 2).

Short segments of pupil data were extracted for each target presentation and then classified as either a *hit* or *miss*. A target was considered a *hit* if it was followed by a button press within 1 s from the presentation; a *miss* was a target presentation without a corresponding button press. The criterion of a 1-s time window was based on preliminary study results on the same visual detection task where all button presses fell within the 1-s window (mean reaction time of 470 ms). Studies in the literature report similar values, ranging between 300 and 550 ms depending on the complexity of the visual discrimination (see, for example, Schroger & Widmann, 1998). If two consecutive targets were less than 2 s apart, only the first pupil segment was evaluated.

For Experiment 1, the average pupillary response across subjects for *hits* is plotted in Figure 3 and is expressed as a change in pupil diameter relative to the time of target presentation. Error bars indicate the 99% confidence intervals for the average pupil profile. For each time sample after the presentation of the target, the corresponding distribution of pupil diameters was compared with a pupil baseline corresponding to the distribution of pupillary data recorded during 1 s preceding the presentation of the target.

Significance testing could be attempted by performing a two-tailed *t*-test against the alternative null hypothesis that

-Experiment 1 : Semantic target detection -

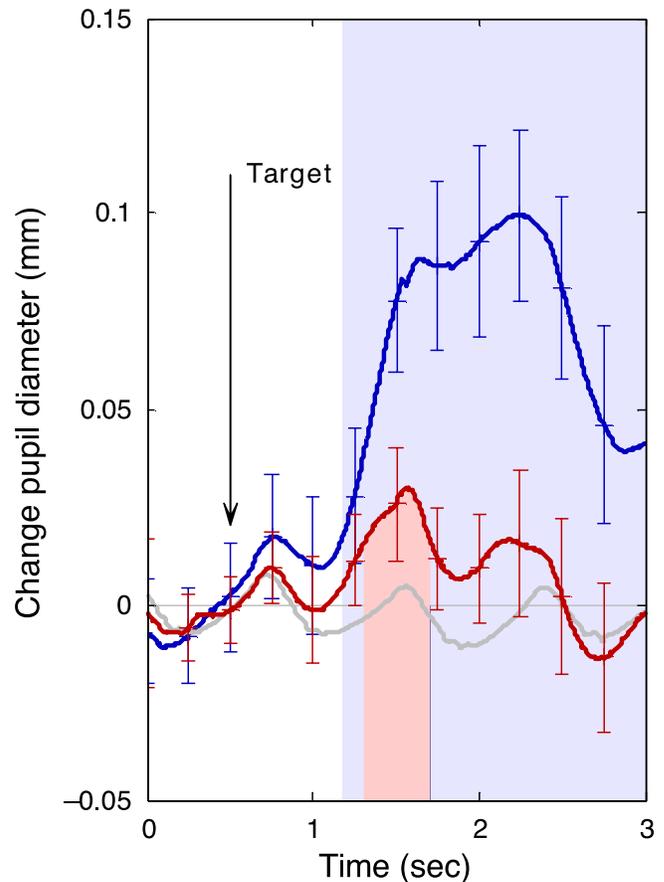


Figure 3. Average of pupil responses for Experiment 1 for two conditions: target detected by button press (blue) and button press not required (red). The vertical arrow indicates the time of target presentation. Error bars correspond to CIs at $\alpha = 0.01$. Shaded sections (light blue for the first condition and light red for the second condition) represent statistically significant ranges (at $p < 0.05$) for dilation when pupil data were compared to a baseline corresponding to 1 s preceding target presentation. The average pupil waveform when no targets were presented to the viewers is superimposed for comparisons (gray periodic waveform).

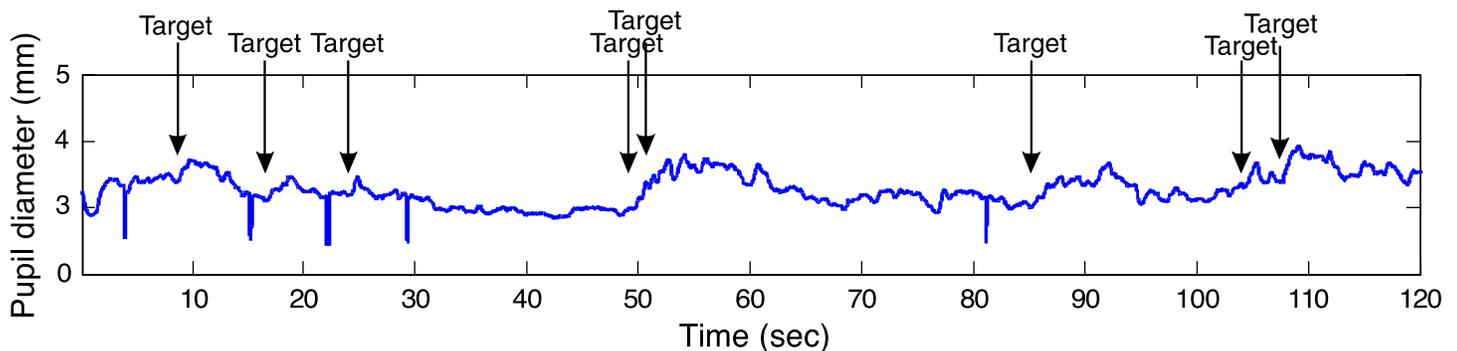


Figure 2. Example of pupil fluctuation during a single viewing session; target presentations elicited pupil dilation detectable in the plot by the enlargement of pupil diameter subsequent to each presentation (vertical arrows).

the pupil mean for each specific time sample after the target is larger (dilation) or smaller (constriction) than the pupil baseline before the display of the target. To avoid the problem of multiple t -tests and the severe penalty of the Bonferroni correction, we used instead a statistical recipe originally proposed by Guthrie and Buchwald (1991) for significance testing of difference brain potentials and then more recently employed in the pupil domain (see, for example, Siegle, Steinhauer, & Thase, 2004). The technique defines a region of the waveform over which a sequence of contiguous p -values could be considered. First, the averaged autocorrelation is estimated in the observed pupillary data after the first PCA components are removed; this was performed only to consider the autocorrelation naturally associated to the pupil resting behavior and eliminating systematic patterns of variation (Guthrie & Buchwald, 1991). The second step implies a Monte Carlo simulation of a first-order autoregressive process using the residual autocorrelations (approximately 0.89 for both experiments) estimated from the experimental data. Finally, the longest sequence of contiguous p -values after target presentation occurring less than 5% of the times in the simulated data (with similar autocorrelation of the experimental data) was utilized as the significance threshold. This sequence defines the length of a temporal window over which a series of contiguous t -test could be considered significant at $p < 0.05$, given the temporal autocorrelation of the pupil waveform; it was 80 ms for both experiments.

Areas of significance are reported as a shaded blue section superimposed on the average pupil profile (Figure 3, blue). Two major events are noticeable: first, a small pupil constriction with onset at approximately 250 ms from the target presentation and followed by a large pupil dilation with onset at approximately 700 ms from the target.

The same time window of 3 s was used to average pupil segments when no targets were presented to, and detected by, the viewers. The corresponding pupil average waveform is superimposed on the same plot (Figure 3, in light gray) and shows a periodicity of 0.7 s, approximately in synch with the presentation of the visual stimuli. Finally (Figure 3), the average pupil segment for the key-press-not-required condition is shown in red; the shaded red section shows the area of significance for dilation.

The visual task proved to be easy in Experiment 1, with viewers detecting all targets. For the second experiment, where targets were missed an average of 23% of the time, the pupil segments were classified as *hits* and *misses* (Figure 4, blue plots are *hits* and red plots are *misses*). Pupil segments were also divided into four categories that were thought to be useful for detecting habituation effects: (i) with low density target viewing sessions (0.1–0.5 Hz, Figure 4, top-left pair of plots), (ii) high density target sessions (0.5–1 Hz, Figure 4, top-right pair of plots), (iii) targets viewed in the first half of a viewing session (bottom-left pair), and (iv) targets viewed in the second half of a session (bottom-right pair).

Pupil dilation was significant for all *hits* (Figure 4); for missed targets, pupil dilation was reduced but still significant in most cases. We also found that the average amount of dilation is lower in sessions with high target frequency and is also decreased toward the end of the session (Figure 5). These results provide evidence that habituation affects the sensitivity of the pupil reflex when viewers are repeatedly exposed to a category of visual targets. The largest dilations were measured for viewing sessions with very few targets or for those targets presented only a few seconds after the beginning of the session (Figure 5). Error bars indicate 99% confidence intervals.

Dividing the data in four different groups, low/high density and early/late presentations (as reported in Figure 4), and considering only the amount of dilation in each pupil segment, we found larger dilations for the high density vs. the low density condition ($p = 0.002$ for *hits* but $p = 0.16$ for *misses*) and for the early presentation vs. the late presentation condition ($p < 0.001$ for *hits* and $p = 0.06$ for *misses*). In general, dilations for *hits* were significantly larger than those for *misses* for three conditions: low density ($p = 0.005$), high density ($p = 0.001$), early presentation ($p < 0.001$) but not for the late presentation condition ($p = 0.2$).

The amplitudes of the dilation were in general small, usually in the range of a few tenths of millimeters and the latency of the dilation onset was widely distributed between 300 and 700 ms. The average shape of the dilation was in agreement with our basic knowledge of the pupil servomechanism; an initial steep dilation (due to sympathetic activity and parasympathetic brain inhibition, see Discussion section) followed by a slow recovery to the initial tonic level (Figures 3 and 4; Privitera & Stark, 2006; Usui & Hirata, 1995).

Mean pupil size was 3.7 mm for all subjects and experiments (5th and 95th percentile equal to 2.6 mm and 5.3 mm). Within this range, the pupil operates in the middle of the iris muscle length–tension curve where the relationship between excitation (input stimulation) and amount of the two smooth iris muscle responses (dilation) can be considered linear (Krenz, Robin, Barez, & Stark, 1985; Privitera & Stark, 2006; Usui & Stark, 1978). As mentioned above, the amount of the target dilations we observed were small (see Figures 3 and 4 for example)—in case of a number of consecutive dilations, the overall pupil size baseline could increase only by a fraction of a millimeter. Within this range, and considering the level of pupillary activity we observed, it is very unlikely that the pupil can approach its biomechanical and nonlinear extremities even when multiple consecutive dilations might have contributed together to temporarily shift the baseline. The decrease of the amount of the dilation at the end of the viewing session or in case of frequent targets we observed in Experiment 2 cannot be attributed to a saturation of the pupil dynamics.

The light pathway must be involved in the mechanism and although the ambient illumination was constant

- Experiment 2 : iconic target detection -

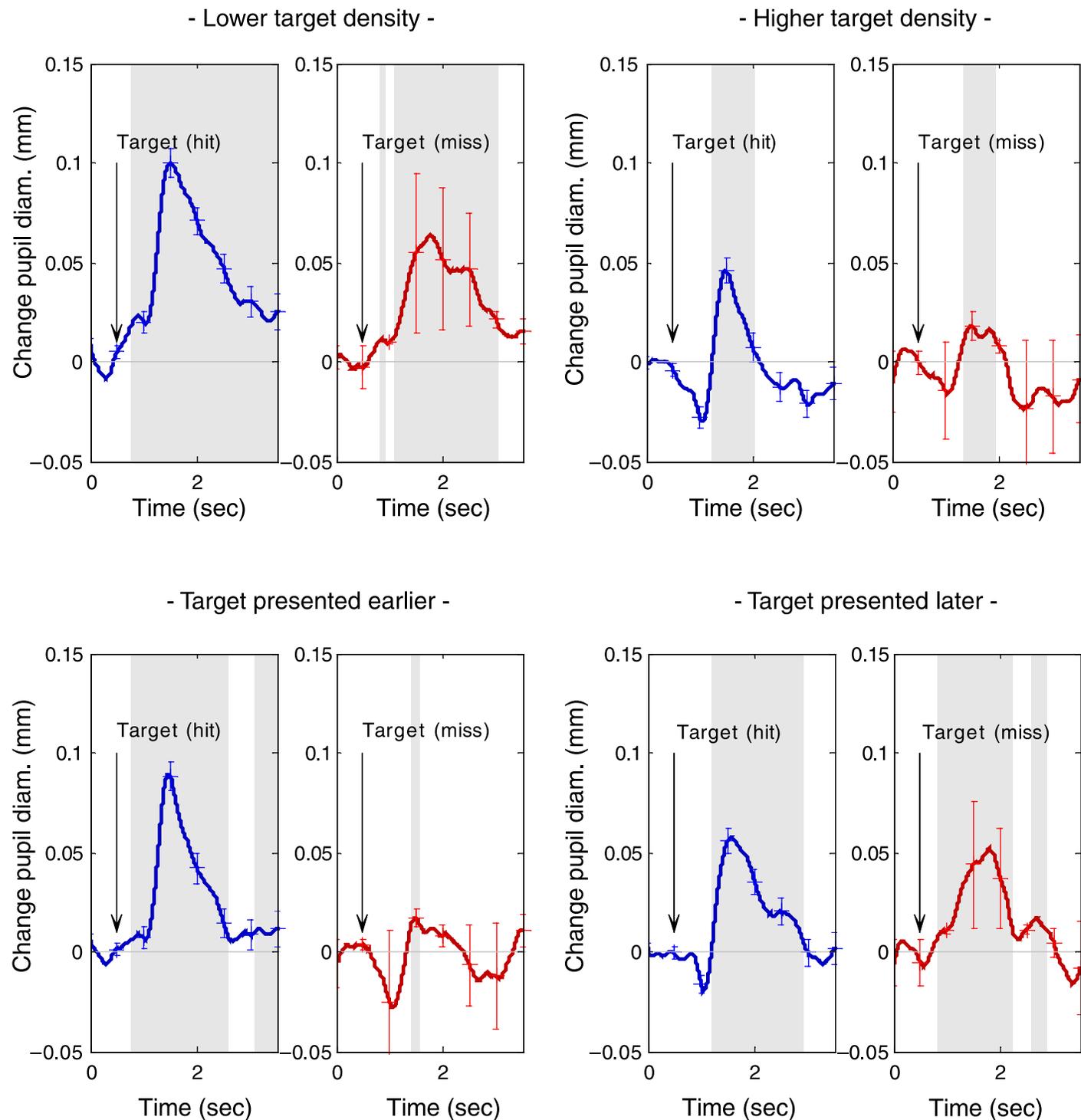


Figure 4. Average of pupil responses for Experiment 2. Data are divided into two groups. In the upper panels, one group is with low target density (few targets per run) and one with high target density (many targets per run). *Hits* (blue line) are pupil profiles when the corresponding target was detected and reported with a button press and *misses* (red line) are the pupil profiles when the target was missed. Pupil dilation is evidenced by a positive peak of the pupil diameter after the target presentation and it is more pronounced in those runs with fewer targets. In the lower panels, one group is for targets viewed in the first half of a viewing session and one for targets viewed in the second half of a session. Targets viewed earlier generated larger dilations. Shaded gray sections represent statistically significant ranges (at $p < 0.05$) for dilation.

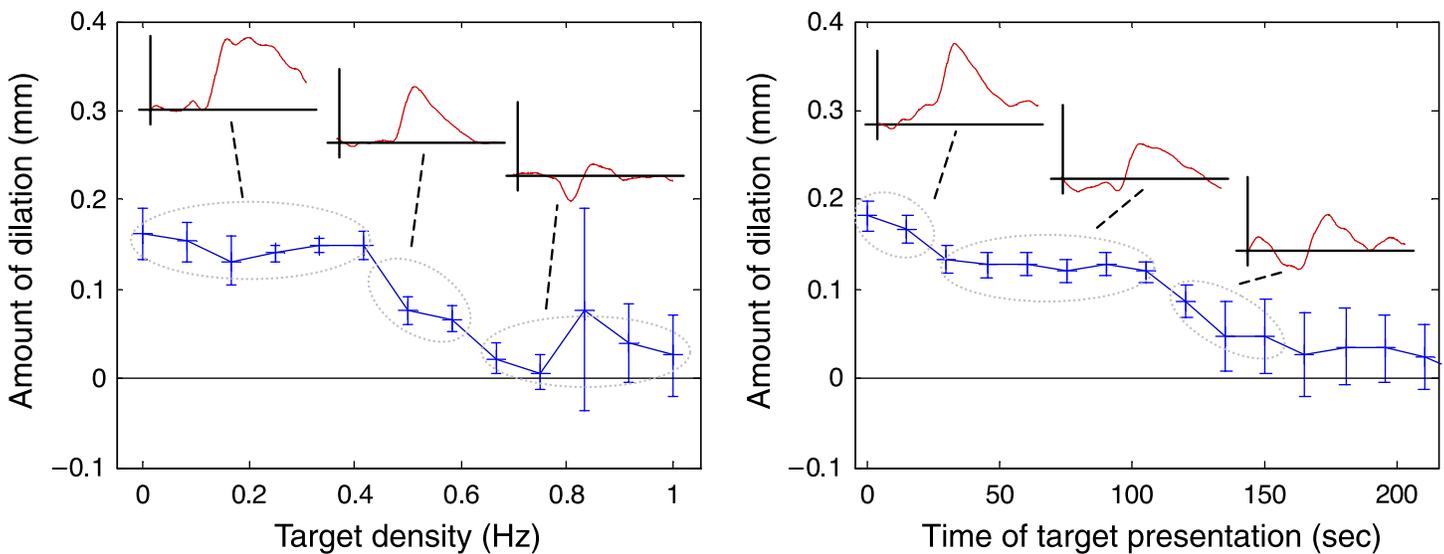


Figure 5. Amount of pupil dilation as a function of (left) target density and (right) time of target presentation. Average pupil waveforms (red insets) for selected ranges of the abscissa (indicated by the dotted ellipses) are inserted on graphs.

throughout the entire viewing session, the computer monitor illumination entered and stimulated the retinal parasympathetic pathway. In the second experiment, where targets and distractors were not all at the same level of brightness, the 10-Hz rapid sequence of photos of variable intensity could generate a pattern of illumination and altered pupil size.

Could the observed dilation to targets have been triggered by a systematic decrease of image illumination? We first compared the foveal brightness between all target and nontarget image chips and also those target chips that were missed at least once during the experiment and we did not find a significant difference in the illumination function. We then looked at the smoothed derivative of the illumination function during the experiment for each stimulus presentation. This was to characterize the pattern of illumination variation of each image: a negative value of the derivative indicates a decreasing step of illumination whereas a positive value indicated increasing brightness. The distribution of derivatives, for target and nontarget images, was not significantly different (mean 0.058 Lux/s and 0.035 Lux/s, respectively, $p = 0.65$), which indicated that there was not a systematic pattern of illumination variation characterizing one of the two stimulus groups.

Button presses identified targets that were explicitly recognized by the viewers. When the button press was not required, the pupil dilations were indeed smaller (Figure 6). In summary, the average dilation for *hit* (target reported by a button press) was larger and lasted longer than the average dilation for *miss* (targets not reported by button press) but presented in sessions where button press was required. For sessions where key presses were not required, pupil dilations were less prominent but still detectable (see shaded red bars, Figure 6, and Experiment 1, Figure 3, also

in red). Note that in the faster paced condition of Experiment 2, the periodic nontarget pupil waveform (due to slower rate of presentation) is not present as it was in Experiment 1; this changed the pretarget pupil baseline for the statistical comparison and made the small dilation for the no button press condition significant (Figure 6, red).

Discussion

The size and dynamics of the pupil depend on a variety of sensory and emotional factors and are controlled by two synergistic pathways that operate on the two smooth muscles of the pupil. The parasympathetic pathway is mediated by the Edinger–Westphal oculomotor complex in the midbrain and innervates the sphincter, which is the circular muscle responsible for constriction. The sympathetic pathway, mediated by the posterior hypothalamic nucleus, innervates the radial dilator muscle of the iris responsible for dilation (Loewenfeld, 1993). It is widely documented that all those mental events, like emotions, fear, physical or cognitive effort, triggering a pupillary dilation response, not only excite the sympathetic pupil dilator pathway but they also inhibit the Edinger–Westphal nuclei thus causing the relaxation of the sphincter muscle contributing to the dilation (Granholm & Steinhauer, 2004; Steinhauer, Siegle, Condray, & Pless, 2004).

Pupil size and pupil dilation have been studied in relation to mental workload and the overall state of alertness or arousal (Bradshaw, 1967; Goldwater, 1972; Granholm et al., 1996; Hoecks & Levelt, 1993; Iqbal et al., 2004; Janisse, 1977; Porter et al., 2007). Pupillography has been successfully employed in monitoring psycho-

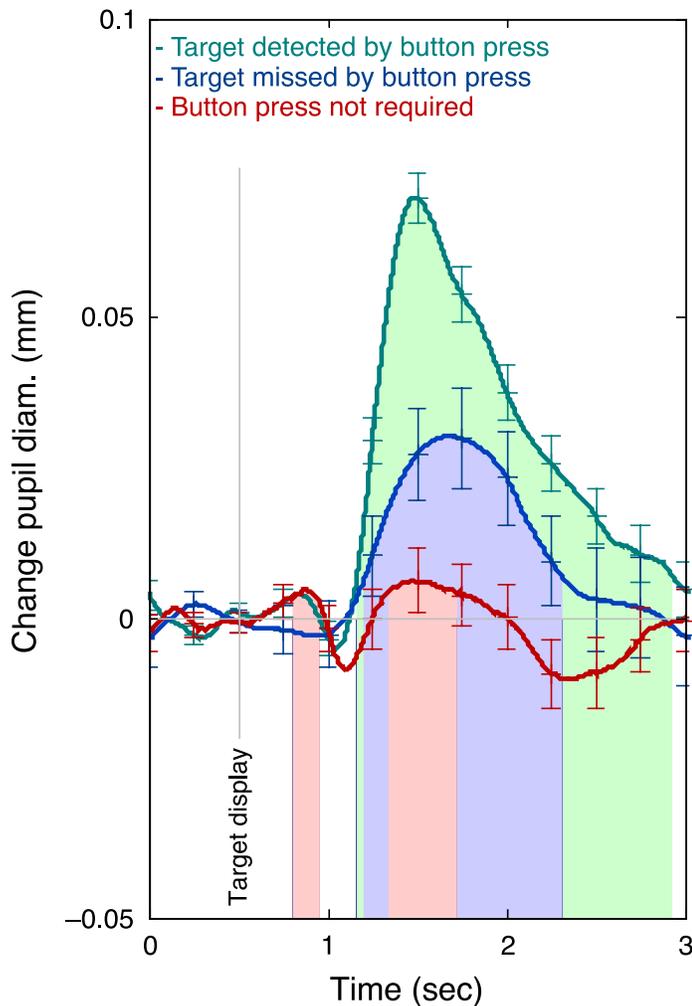


Figure 6. Average pupil dilation for the three different viewing conditions. Shaded color sections represent statistically significant ranges (at $p < 0.05$) for dilation for the three conditions. Time of target presentation is indicated by the gray vertical line.

cognitive activity in many perception experiments such as speech or word recognition, reading and simple auditory tests (O'Neill & Zimmerman, 2000; Steinhauer, 2002). Here, we documented how the pupil responds when a visual target or an object of interest is detected, recognized, and must be acted upon by an observer.

The two experiments differed in task difficulty. In both experiments, viewers were asked to attend to a sequence of scenes and to recognize specific object categories. In the first experiment, stimulus presentation rate was slow and the stimuli were easy to discriminate from the background. Subjects were informed only about the general meaning of the object they had to detect and not about its specific name or iconic conformation. We called this *semantic* visual detection since the experiment required a rapid visual inference where each stimulus had to be recognized and semantically elaborated. This type of condition is commonly encountered during natural viewing conditions where stimuli must be often perceived

and interpreted based upon a specific context or cognitive task.

The pupil response in [Experiment 1](#) is characterized by two important and distinct events ([Figure 3](#), blue). There is an initial constriction of the pupil whose onset is approximately at 200 ms from the presentation of the target that is then followed by a larger response, a dilation whose onset is approximately 700 ms from the presentation of the target. The pupil's response to a sequence of nontarget images is characterized by a periodic sequence of small constrictions in synch with the presentation rate. These small periodic constrictions cannot be light-triggered constrictions as the stimuli used in [Experiment 1](#) were iso-luminant. We know that the cortex can exercise an influence on the pupil through direct projections to the parasympathetic Edinger–Westphal nucleus in the mid-brain and the pupil can indeed respond to nonluminosity stimulus attributes such as spatial structure, color transient, or coherent movement (Barbur, 1991, 2004; Conway, Jones, De Bruine, Little, & Sahraie, 2008; Wilhelm, Wilhelm, Sancho, & Barbur, 2002). The transition between different images in the sequence generates spatial frequency and motion transients that could trigger a small pupil constriction for nontarget visual images. This is particularly true in the first experiment where the sequence of images was slow and well within the pupil frequency bandwidth. It is plausible to assert that the periodic oscillation in the nontarget pupil waveform ([Figure 3](#), gray waveform) and the small initial constriction in the presence of target ([Figure 3](#), blue) is driven by changing low level attributes of the stimuli.

For target detection, the small and early pupil constriction is immediately overcome ([Figure 3](#), blue) by the opposite and stronger pupil dilatory movement that is driven by the slower sympathetic limbic pathway (Loewenfeld, 1993, Chapter 6; Usui & Hirata, 1995) and supported by the parasympathetic inhibitory component (Granholm & Steinhauer, 2004; Steinhauer et al., 2004).

The second experiment was more challenging, with satellite imagery of urban and rural areas displayed in a rapid sequence (10 Hz). The helipad targets were characterized by clear visual features, an open white paved space with a large centered “H”, with which the subjects were familiar. In this *iconic* visual detection task, significant pupil dilation occurred after target presentation with an onset time ranging between 300 and 700 ms ([Figure 4](#)). The early small constriction was still noticeable but not as prominent as in [Experiment 1](#). Most importantly, the amount of dilation varied as a function of target density and the time of target presentation in the viewing session. Larger dilations occurred for targets viewed earlier in the session and for sessions with fewer targets. Habituation, surprise, or uncertainty are all factors somehow related to each other and may all be involved in the progressive decrease of perceptive sensitivity due to repetition of a stimulus. The importance of uncertainty has been reported in other pupil studies; for example in

auditory perception the amount of pupil dilation for target recognition was found to be increased for less probable sound targets (O'Neill & Zimmerman, 2000, see also Friedman, Hakerem, Sutton, & Fleiss, 1973; Qiyuan, Richer, Wagoner, & Beatty, 1985) and it was found to be in general proportional to the habituation or progressive level of familiarity with the stimulus (Steinhauer & Zubin, 1982). Our experiments showed evidence for a similar behavior for visual detection.

Pupil dilation in response to psychological stimuli is principally controlled by the sympathetic limb of the autonomic nervous system that originates in the hypothalamus. The limbic system is reciprocally connected to the visual pathway in the cortex in a complex manner. In everyday viewing, targets are recognized without necessarily a concomitant motor response (the initialization of which occurs later in the frontal motor area), but the recognition could still trigger pupil dilation depending on the targets significance. In the second experiment where subjects generated many *misses* (even if fixation was always maintained on target), the average pupil profile after a *miss* was characterized by a weaker, but significant, pupil dilation (Figure 4). The finding of a significant dilation to targets not reported with a button press is one of the most surprising findings of this study. During the brief target presentation, the observer may see the target but be subconsciously uncertain of its identity and ultimately decide to not press the button. While the target may be detected and a pupil response elicited it may still not reach the criterion of certainty for a button press. The pupil response being essentially a continuous variable might encode identity certainty whereas a button press is a binary response with perhaps a relatively high criterion. Our finding contrasts with those of Hakerem and Sutton (1966) where dilations were observed only when the target was seen and reported.

In the control experiment where a button press was not required, the pupil dilation to targets was still significant but attenuated (Figure 6, red) as compared with *misses* in the button press experiments. It is unclear why the pupillary response in the “silent” detection task (i.e., no button press) is weaker than during a missed target during the button press task. It may reflect the observers’ motivation or level of participation involved in decision-making (see Einhäuser, Koch, & Carter, 2010; Simpson & Hale, 1969, and Discussion section below). In a task with button presses, the observer is very task involved and that may well evoke larger pupillary responses.

Noradrenaline released by the locus coeruleus, LC, has a modulating role in perception and cognition with enhancing effects on perceptual acuity, attention, memory, and decision processes (Aston-Jones & Cohen, 2005; Bouret & Richmond, 2009; Bouret & Sara, 2005; Sara, 2009). In situations of high uncertainty, it has a role in consolidating and supporting the decision within the competent cortical areas (Bouret & Sara, 2005; Einhäuser et al., 2010).

It is known that arousal elicits pupil dilation (Bradshaw, 1967; Loewenfeld, 1993) and the tight correlation between pupil diameter and LC activity has been widely reported recently (Aston-Jones & Cohen, 2005; Sterpenich et al., 2006); LC phasic responses to a perceptually relevant event (Richer & Beatty, 1987) or to the level of task engagement (Gilzenrat, Cohen, Rajkowski, & Aston-Jones, 2003) are correlated with pupil dilation. Recent studies provide evidence for the role of the noradrenaline–LC complex and, thus, on the occurrence of a pupil dilation, in pure cognitive processes such as perceptual rivalry (Einhäuser et al., 2008) and perceptual decision processes (Einhäuser et al., 2010).

Our results on pupillary dilation in visual search are consistent with the notion of LC activation in decision processes. The presence of a weaker pupil response in the absence of a consequent motor contingency (Experiment 1 and Figure 3, red; Experiment 2 and Figure 6, red) was also discussed by Einhäuser et al. (2010) and agrees with the idea that the strength of LC activity is correlated with the behavioral consequence of the stimulus (Bouret & Richmond, 2009; Simpson & Hale, 1969).

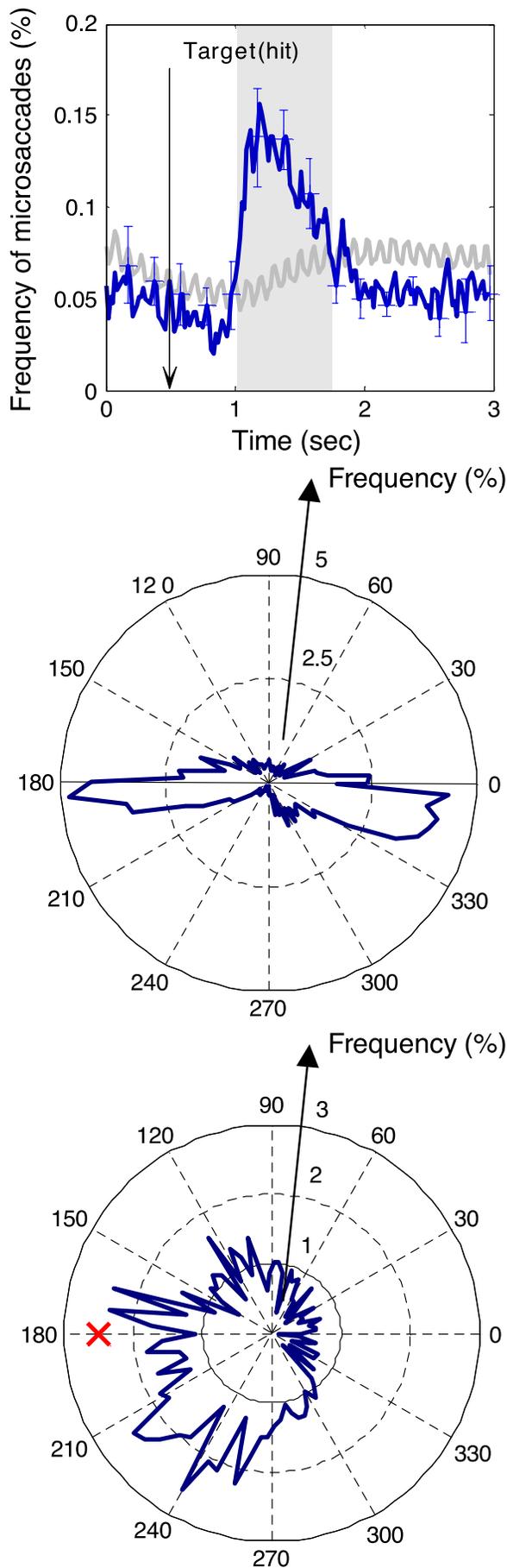
The presence of a pupil response to targets that were not identified as detected by a button press likely reflects uncertainty in the decision process and might indicate a role for noradrenaline in subconscious decisions. As mentioned above, the button press is a binary variable that when pressed reflects reaching a threshold criterion whereas LC activation may approximate a continuous variable with detectable effects at subthreshold levels well below the level needed for the behavioral decision.

To conclude, the human pupil responds with dilation to visual detection. The amount of dilation is smaller at high target presentation rates and for targets viewed later in a repetitive sequence. We found pupil dilation even when viewers did not report seeing the targets and dilation was influenced by, but not depending upon, the requirement of a button press.

Appendix A

Eye movements and blinks

We checked the eye movement data and confirmed that eye position was maintained within an average radius of 5.4 arcmin (std = 11.3) of visual angle around the fixation point. Major drifts or saccades directed eccentrically from the central fixation point intervened occasionally, but they did not correlate with any specific characteristic of the scenery viewed during their occurrence and they were eliminated by the analysis described below. We know that fixational microsaccades occur naturally even when fixation is maintained (Carpenter, 1988) and we found a small but significant increase of the frequency of the microsaccades in the presence of targets (Figure A1, top



panel, shaded areas show region of significance). Microsaccades were defined by a peak velocity of at least $8^\circ/\text{s}$ (Bahill, Clark, & Stark, 1975; Engbert, 2006) and their increase for targets does not come as a surprise; the complex relationship between microsaccades and visual attention during fixation visual tasks is well known although not fully understood, and it remains an active area of research (Engbert, 2006; Horowitz, Fine, Fencsik, Yurgenson, & Wolfe, 2007; Tse, Sheinberg, & Logothetis, 2002). Microsaccades are associated with shifts of covert attention in cuing experiments (Engbert, 2006; Hafd & Clark, 2002), but they are also reported in fixation tasks as a response to a stimulus change without any instructions for attentional cuing (Engbert & Kliegl, 2003) or even in the presence of visual and auditory integration of attention (Rolfs, Engbert, & Kliegl, 2005).

Fixational microsaccades or major drifts might have a minimal instrumental effect on pupil size; however, they are mostly distributed along the horizontal axis (Figure A1, middle panel) equally oriented either to the left or to the right and thus the effect on the pupil cancels out. We verified this by checking the distribution of the delta pupil sizes for all the fixational microsaccades measured after target presentation, and indeed, we have not found a significant trend (zero mean, $p = 0.58$); this rules out the possibility that fixational microsaccades had a systematic and artifactual “dilation” effect on the measurement of pupil diameter. A similar distribution of fixational microsaccades was observed for the nontarget stimuli, but their rate did not show the same modulation after stimulus presentation (Figure A1, top).

The predominance of a horizontal component of microsaccades has been reported elsewhere and it is attributed to the structure of the neural circuitry in the brain stem circuitry responsible for saccade generation (Engbert, 2006). The last graph (Figure A1, bottom panel) was generated by rotating each vector representing a microsaccade by the angle subtending the origin of that microsaccade and the center of the screen (and center of the target) so that the position of the target (Figure A1, bottom, red “x”) appears in the graph always at 180 degrees

Figure A1. (Top) Frequency of microsaccades during fixation shows a modulation in the presence of the target (blue line; nontarget frequency is reported in gray). The vertical arrow indicates the time of target presentation. Error bars correspond to CIs at $\alpha = 0.01$ and the shaded gray section represents statistical significance. (Middle) The frequency of the direction of microsaccades (corresponding to the area of significance, shaded gray section, top) shown in polar coordinates has a strong and equally distributed horizontal left and right components. (Lower) Frequency of microsaccade direction with respect to the relative position of the target (red “x”) and the starting position of the microsaccade (center). Target onset caused an increase of “micro-corrective” microsaccades directed to the center of the screen (and center of the target), i.e., a “refixation” of the stimulus.

with respect to the point of origin of the saccade (center of the polar coordinate space, [Figure A1](#), bottom). Not surprisingly, fixational microsaccades were planned predominantly toward the part of the field of view containing the center of the target corresponding to the two quadrants on the left in the graph ([Figure A1](#), bottom).

Eye blinks have been studied in cognitive and psychology experiments and mental effort has been correlated with fewer and shorter blinks (Goldstein, Bauer, & Stern, 1992). We analyzed blink frequency for target and nontarget presentations and found a short decrease of blink frequency more than 1 s after target presentation that never reached significance.

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